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A case study of MgB_2 and HTS magnets being cooled and cooled down using a hydrogen thermal-siphon cooling-loop with coolers

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Abstract

When one fabricates a magnet using MgB_2 or HTS conductors, the operating temperature of the magnet can be increased into the temperature range from about 15 to 30 K. This temperature range is between the triple-point (13.8 K) and the critical point of para-hydrogen (32.3 K). Hydrogen has excellent heat transfer properties both as a liquid and as a gas at low temperature. The heat of vaporization of hydrogen is larger than any cryogenic fluid. In addition, the specific heat of the liquid and the gas is higher than any cryogenic fluid. Hydrogen may be the best fluid to use to connect a magnet operating between 15 and 30 K with a source of refrigeration. This paper compares magnet cooling at 20 K using helium and hydrogen. A safe completely passive cooling loop is discussed in this paper.

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Keywords: Hydrogen; Helium; MgB_2; Magnet; HTS Magnet; Thermal-siphon Cooling Loop

1. Introduction

Thermal-siphon cooling loops have been used to cool superconducting detector magnets since the 1970's [1]. This involved using natural convection and the phase separation of helium gas from liquid helium to drive the cooling loop. A refrigerator produced the liquid helium and took back the cold gas. MRI magnets and other types of magnets have been kept cold using re-condensers connected to the cooler cold head [2]. Thermal-siphons have been used in conjunction with condensers to ensure that cold liquid helium enters the system at the bottom, which

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maximizes the efficiency of the cooling process [3]. With such systems the cool-down a cryostat and liquefaction of helium into that cryostat was demonstrated using small coolers [4].

The cyclotron gas stopper magnet at Michigan State University (MSU) uses six pulse tube coolers (three for each coil) that generate 1.35 W at 4.2 K on each cooler second-stage while producing 36 W of cooling on each first stage to cool-down and keep cold a 2500 kg of total cold mass [5] [6]. This magnet was tested in 2014 and 2015 [7]. This paper discusses whether this technique can be used to cool-down, liquefy, and keep the magnet cold using hydrogen as a working fluid instead of helium. A number of people have proposed hydrogen cooling HTS magnets [8], [9]. A passive liquid hydrogen thermal siphon cooling loop, using a two stage cooler 4 K was discussed by Green [10] in 2013. This paper compares a hydrogen-cooled magnet with a helium-magnet of the same size and mass as the MSU cyclotron gas-stopper magnet, which took ~14 days to cool-down with helium at 2 MPa.

2. Why use liquid hydrogen cooling HTS and MgB_2 magnets?

Para-hydrogen is in the liquid state from 13.81 K (triple point temperature) to 32.3 K (the critical temperature) is potentially attractive for cooling MgB_2 and HTS magnets. If two-phase hydrogen is used in a passive cooling loop cooled by a cooler, the magnet temperature can be kept at a constant temperature that is within 0.2 to 0.3 K of the cooler cold head temperature. Liquid hydrogen has the highest heat of vaporization of any cryogenic fluid. The C_p of hydrogen is the largest for any gas or liquid. Table 1 compares the properties of helium and hydrogen. Hydrogen is a potential fluid for use in a thermal-siphon cooling loop for cooling down, liquefying and keeping a magnet cold.

Table 1 Helium and Hydrogen Parameters [11]

Parameter	Fluid He	Fluid H_2
Triple Point T (K)	2.17	13.81
Triple Point P (kPa)	5.1	7.0
Boiling T T_b at 101.3 kPa (K)	4.22	20.4
Liquid Density at T_b (kg m^{-3})	125	70.8
Critical T (K)	5.19	32.3
Critical P (kPa)	221	1292
Heat of Vaporization (J g^{-1})	20.9	442
C_p Liquid at T_b (J g^{-1} K^{-1})	~2.5	~9.8
C_p Gas at T > 2T_b (J g^{-1} K^{-1})	~5.2	~14.2
k_f Liquid at T_b (W m^{-1} K^{-1})	0.027	0.119
k_f Gas at T_b (W m^{-1} K^{-1})	0.011	0.021
μ liquid at T_b (kg m^{-1} s^{-1})	3.5x10^{-6}	1.3x10^{-5}
μ gas at T_b (kg m^{-1} s^{-1})	0.9x10^{-6}	1.1x10^{-6}
Max Nucleate Boiling Q (W m^{-2}) [12]	~8000	~90000
Film Boiling h_c (W m^{-2} K^{-1}) [12]	~670	~330

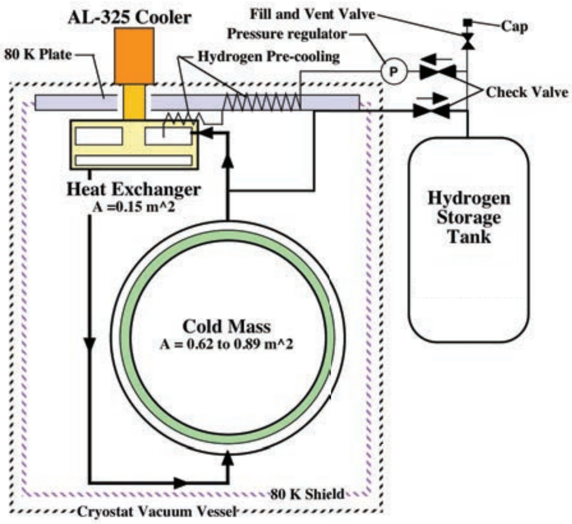

Figure 1. A schematic diagram of a hydrogen Thermal-siphon cooling-loop for a magnet

3. A passive two-phase hydrogen cooling loop with a single-stage cooler

Figure 1 above shows a simplified version of a passive liquid hydrogen cooling-loop. The cooling-loop is filled with hydrogen gas and capped before the cold mass is cooled down. The size of the hydrogen storage tank is a function of the amount of liquid hydrogen that is produced by the cooler [10]. For 3.0 L of LH_2 at 20 K, the tank size is ~250 L at a pressure 1 MPa. The use of a passive cooling loop avoids most of the flammable gas safety hazards associated with hydrogen [13], [14]. The cooler shown in Figure 1 is a Cryomech AL-325 single-stage GM cooler [15]. This cooler produces 0 W at 11 K, ~70 W at 20 K, ~140 W at 30 K ~230 W at 50 K and 290 W at 90 K.

One must prevent the cooler cold head from being at a temperature <15 K to avoid frozen hydrogen. The downside of this cooler is the short maintenance interval for a GM cooler (~10000 h).

The cyclotron gas stopper magnet cool-down took longer than expected [6], [7]. The reasons for this were: 1) the cooling passages around the coil were very tight; 2) the flows through the cooler heat exchangers were uneven due different pipe sizes; and 3) the cryostat pressure during the cool-down was limited by the bellows in the piping. The model created at Michigan State University predicted the cool-down time for a single coil and cryostat with a total cold mass of 1250 kg [7]. This model was used to predict the performance of a natural convection thermal-siphon cooling loop designed for hydrogen as well as helium. The model was run with both hydrogen and helium to model a cool-down from 300 K to 20 K. Two different coil passage configurations were used. A configuration with small cooling passages is shown in Figure 2. A configuration with larger cooling passages is shown in Figure 3.

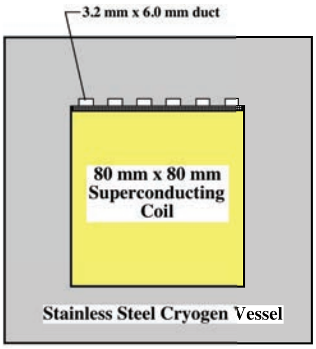

Figure 2. A superconducting coil system with six 3.2 x 6.4 mm cooling-ducts. The total flow area is 123.9 mm^2. The total inner surface area is ~0.89 m^2.

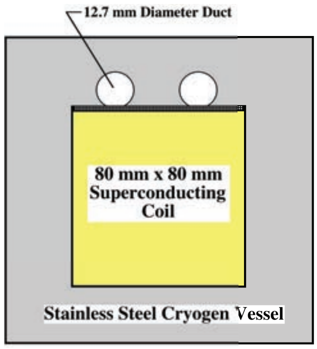

Figure 3. A superconducting coil system with two 12.7-mm diameter cooling-ducts. The total flow area is 253.4 mm^2. The total inner surface area is ~0.62 m^2.

For a given mass flow rate of helium or hydrogen, the configuration in Figure 2 will have a pressure drop that is from 4 to 6 times higher (depending on the Reynolds number in the passages) than the configuration in Figure 3. A factor of two increase of pressure within the flow channels decreases the pressure drop a factor of two for a given mass flow. In a natural convection circuit, an increase in pressure increases the driving pressure. Both effects will increase the fluid mass flow in the circuit to remove heat more rapidly from the cold mass.

Figure 4 shows the cool-down time for a single cold mass (1250 kg) attached to a single AL325 cooler, for He and H_2 flowing through the passages shown in Figure 2. Figure 5 shows the cool-down time for the same coil through the passages shown in Figure 3. At the end of the hydrogen cool-down, the pressure is reduced to 0.1 MPa so that the hydrogen can get down to ~20 K without liquefaction. (At 0.4 MPa, hydrogen liquefies at ~26 K).

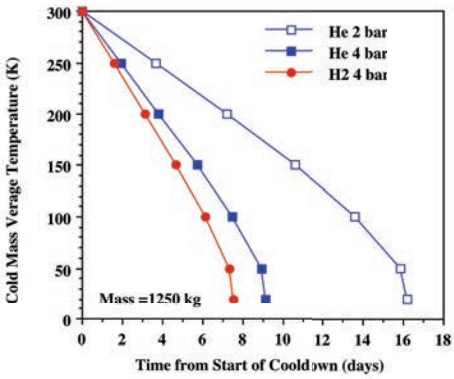

Figure 4. Magnet temperature versus time and cryostat pressure during a cool-down through six 3.2 x 6.4 mm cooling-ducts. The squares are with He gas; the circles are with H_2 gas.

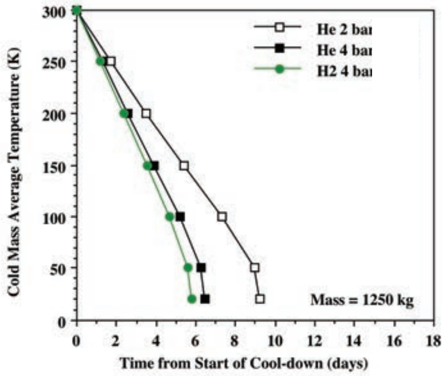

Figure 5. Magnet temperature versus time and cryostat pressure during a cool-down through two 12.7-mm diameter cooling-ducts. Squares are with He gas; circles are with H_2 gas.

A passive circuit like the one shown in Figure 1 must be designed to have a working pressure of >1.2 MPa. In all cases, the use of hydrogen in the thermal-siphon loop reduced the cool-down time because its mass flow is lower by a factor of 2.7 for a given amount of refrigeration, because of hydrogen's larger specific heat. The density of hydrogen gas is a factor of two lower than for helium, but there is still a net gain in the rate that heat is removed from the cold mass. The reduction of the cool-down time using hydrogen in the place of helium is not as large as the cool-down time reduction caused by doubling the pressure in the cooling channel. Pipe friction and the density head available to drive the free-convection flow circuit dominate the rate of heat removal from the cold mass by the cooler. The heat transfer area within the magnet cryostat doesn't appear to be an important factor.

If the hydrogen gas entering the cryostat is pre-cooled to 90 K by the liquid nitrogen shield, it takes ~1740 J of cooling to liquefy 1 g of hydrogen gas. (This assumes that the ortho to para transition occurs between 90 and 20 K.) With 70 W of cooling at 20 K, the hydrogen liquefaction rate is ~2 L h^{-1} (assuming 100 percent efficiency). Even with the inefficiencies in the system, the liquefaction of the hydrogen in the loop takes much less time than cooling the cold mass from 300 K to 20 K. Once the hydrogen has been liquefied the MgB_2 or HTS coil can be kept at a constant operating temperature (within 0.2 to 0.3 K [16]) in the temperature range from 16 K to 28 K.

4. Concluding comments

The use of liquid hydrogen for cooling magnets with MgB_2 and HTS conductors appears to be doable. There is a reduction in the cool-down time for a given configuration when hydrogen is used in a cooling loop. Liquid hydrogen has the advantage of providing a stable magnet temperature that is very close to the cold head temperature in the range of temperatures between 16 K and 28 K. This is not possible for a helium-cooled magnet at these temperatures. The size of the cooler needed to cool a magnet at liquid hydrogen temperature depends on the heat load and the desired cool-down time. Passive circuits such as the one shown in Figure 1 are likely to pass muster with a hydrogen safety committee as long a the hydrogen system is fabricated in accordance with the flammable gas pressure vessel code and other codes applicable to hydrogen. The key is limiting the total liquid hydrogen inventory to the small amount, so that the hydrogen can be stored at high pressure in a tank without venting to the atmosphere.

Acknowledgements

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